



Involvement of concrete internal potential to reduce portland cement consumption and ensure sustainable development

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Abstract. Protection of artificial human habitat from negative impacts of external environment and extension of service life of building structures become priority tasks of structural concrete improvement. The most important vector of development is the increase of their strength due to involvement of the internal resources with minimal use of additional external ones, which corresponds to the sustainable development concept. However, practice shows that now application of high-strength concretes, which are the main focus of researchers, is very limited due to insufficient development of production infrastructure, regulatory documentation, design and construction methods, economic and other reasons.

At the same time, approximation to requirements, according to the sustainable development concept, for the most widely used concretes with grade strength classes (B20-B50) is required right now. In this regard, the idea of application of the most important principles of obtaining high-strength self-compacting concretes in the manufacture of medium strength material is relevant. The article presents the main stages of research on development of the design methodology of medium strength classes self-compacting concretes with reduced Portland cement consumption.

The methodological basis for designing these concretes is the successive introduction of additional components principle while recording their effect on the material properties. The use of ground quartz sand as a mineral additive is due to the concrete mix stability requirements and its widespread availability, which allows for the practical application of the obtained results with minimal barriers and contributes to the reduction of CO₂ emissions. It has been established that when selecting sand fineness of 180...220 m²/kg and a fixed amount of active mineral additive (7.5%), the compressive strength of the cement paste can be reduced to the following linear dependence: $R_{\text{binder}}^{28} = 118.9 - 0.22CM$. Rational contents of fine and coarse aggregates have been identified, and their quantitative effect on the strength of the resulting concrete has been established. It has been established that the obtained concretes with increased efficiency of Portland cement using can be used in practice in various construction areas, and are also necessary for the search and transparent monitoring of the influence of others, more reactive mineral additives based on industrial products and rocks.

Keywords: reducing in cement consumption, self-compacting concrete, mineral additives, concrete mix composition calculation method

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1. INTRODUCTION

Protection of the artificial human habitat from negative environmental impacts and extension of the service life of building structures are becoming a priority area of construction materials science. The most suitable material, allowing to control properties, is concrete. The most important vector of concrete technology development is increasing in strength by using internal resources with minimal involvement of additional external ones. This makes the use of Portland cement (PC), which is a concrete component (including due to the possibility of reducing in the cross-section of more durable concrete structures), more efficient and meets the requirements of the sustainable development concept. The result of research in this area is the design of composites known as High-Performance Concrete (HPC) and Ultra High-Performance Concrete (UHPC) [1–3]. Such concretes are close in their properties to natural functional analogues – durable rocks, while possessing high technological effectiveness in giving the required shape and compatibility with reinforcement and other materials [4–6]. However, in practice, the use of HPC at this stage is very limited due to the insufficient production infrastructure development, regulatory documentation, design and construction methods, economic and other reasons [7]. At the same time, increasing the compliance of the most popular conventional concretes (grade classes of B20-B50) with the requirements of sustainable development is required right now. In this regard, the idea of applying the most important principles of HPC production in the manufacture of conventional concrete becomes logical. This will ensure a reduction in PC consumption with a neutral or positive effect on strength and, as a result, reduce CO₂ emissions associated with its production, increase the durability and manufacturability of the material by improving the concrete structure at the micro- and macro- levels.

The main principles of HPC production are based on optimization of composition, structure and technological parameters [3, 5]. One of the most rational options for practical implementation of this idea is the use of highly efficient self-compacting concrete (SCC), based on the control of rheological properties to achieve the required flowability, resistance to stratification and the ability to fill the formwork without vibration [8-11]. The following key aspects of SCC are confirmed by scientific research:

1. Optimization of rheological properties [11]. High concentration of superplasticizers (2–3% of the PC wt) based on polycarboxylate ethers provide low viscosity and pseudoplastic behavior. Viscosity modifiers (e.g. methylcellulose) prevent fillers sedimentation.

2. Granulometry of fillers [12, 13]. Increased content in fine fractions (quartz sand with fraction of ≤ 0.5 mm and microsilica) improves particle packing, reducing friction between them. Limitation of coarse aggregate by size and quantity (maximum size is 16–20 mm) minimizes blocking when passing through the reinforcement framework.

3. Control of water-cement ratio (W/C). $W/C \leq 0.35$ in combination with superplasticizers ensures self-flowing of the mixture without stratification. The use of microsilica (5–10%) [14, 15] compensates for the decrease in workability at a low W/C ratio.

4. Stabilizing mineral additives. Fly ash (20–30%) and ground granulated blast furnace slag (GGBS) increase of the mixture cohesion and reduce heat evolution. Limestone dust (up to 15%) improves stress distribution in fresh mixture [9, 16, 17].

5. Durability and environmental friendliness. Reducing porosity due to pozzolanic additives increases resistance to chlorides and sulfates [18]. PC replacing with industrial waste (fly ash, GGBS) reduces the carbon footprint by up to 50% [16, 17].

Most of the above aspects can be implemented in the production of not only HPC, but also materials with medium compressive strength, which will be discussed further in this manuscript.

According to a number of experts [19, 20, 21], one of the most important conditions for increasing the service life of concrete-based structures is to give them self-healing ability. Despite high compressive strength, this material has a relative fragility, a reduced coefficient of transverse deformation (or Poisson's ratio), which entails the risk of cracking and the structure destruction. It should be taken into account that the declared above reduction in PC consumption with an increase in the efficiency of its use is a factor that potentially reduces the self-healing ability. In this regard, the goal of this research is to develop a scientific and theoretical concept for the creation of self-healing high-strength building composites for the design and construction of durable and environmentally friendly buildings and structures.

This manuscript shows the first stage of research is to create an effective PC based system for further modification, i.e. the development of a methodology for designing self-compacting concretes of a wide range of grade classes in strength with reduced PC consumption.

2. METHODS AND MATERIALS

The compressive strength of the samples was tested using a laboratory press with a load of 100 tons.

The basic material of the designed concrete was commercial PC CEM I 42.5 N (Manufacturer: Verkhnebakansky Cement Plant, Novorossiysk, Russian Federation). Mineral composition of Portland cement: C_3S - 62%, C_2S - 15%, C_3A - 7.0%, C_4AF - 14%. Grinding fineness - 340 m^2/kg , residue on sieve 008 - 3.5%, water demand - 26.5%, start of setting - 120 min., end of setting 360 min. The concrete modifier MB 0-50S (LLC "Master Concrete Enterprise") was used as a pozzolanic additive. It consists of a mixture of fly ash and microsilica in a ratio close to 1:1, with a minimum organic component content (superplasticizer S-3). The abbreviation of this modifier is further in the manuscript is CM (concrete modifier). Quartz sand (Manufacturer: Formmaterialy, Voronezh) with a fineness modulus of about 1.5 was used as a fine aggregate and raw material for obtaining a mineral additive. Granulometric composition of quartz sand: 0.16 mm - 41%; 0.315 mm - 45%; 0.64 mm - 14%. The content of clay and dust particles is no more than 0.5%, the density in a loose state is 1315 . Crushed stone of fraction 5–10 mm from quartzite sandstone of Lebedinsky GOK (Belgorod region, Russian Federation) was used as a coarse aggregate. The bulk density of quartzite sandstone crushed stone is 1413 kg/m^3 , chemical composition: SiO_2 - 86.24%, TiO_2 - 0.27%, Al_2O_3 - 2.39%, Fe_2O_3 - 2.16%, FeO - 1.58%, CaO - 0.89%, MgO - 1.34%, $Na_2O + K_2O$ - 0.64%, P_2O_5 - 0.11%. Grinding of quartz sand was carried out in a laboratory ball vibratory mill with a loading of 5 kg. Control of grinding fineness was carried out according to the Blaine method with a device of the PMC type. The abbreviated designation of the final product hereinafter in the manuscript is GS (ground sand).

When designing concrete using a Fungilab EVO rotational viscometer, the average value of the viscosity of the cement paste was determined at disk rotation frequencies, simulating the speed of the mixture free flow at different surface slopes. Concrete samples were molded at $W/C = 0.2$. The content of superplasticizer: the MC Bauchemie PowerFlow 3100, was adopted for all concrete mixtures as a constant: 0.6% of the binder amount.

The following sequence of mixture preparation was adopted in the study: dry components of the binder were pre-mixed and then mixed with water, maintaining $W/C = 0.2$. The resulting mixture was stirred and held for 5 minutes. Then the required amount of liquid plasticizer was added to the mixture, and the mixture was stirred until it was completely liquefied for 4-5 minutes. In cases where fine aggregate (FAC) and coarse aggregate (CAC) concretes were produced, the required amount of appropriately prepared aggregate was added to the resulting cement paste. All mixes were hardened during the first day (before stripping) in air-humid conditions at a relative humidity of 95%, at least, and then were hardened in water.

Cubes of $2 \times 2 \times 2$ cm and $7 \times 7 \times 7$ cm were used to assess the strength characteristics at different ages. All mixes were prepared mechanically using a hand mixer with nozzles of different sizes. Important features of the mixture preparation process at different stages of the study are discussed further in the manuscript.

The microstructure of the cement paste samples was studied using scanning electron microscopy. The scanning electron microscope Mira 3 FesSem (Tescan, Czech Republic) was used as a tool, operating in high vacuum mode (InBeam) using a high-brightness Schottky cathode. The samples were sputtered with chromium. The samples strength was tested using a laboratory press with a load of 100 tons.

3. RESULTS AND DISCUSSION

Based on the basic principles of HPC production, a significant reduction in PC consumption in concretes with the most popular grade classes in strength can be achieved by forming a self-ordering high-density structure at the micro level according to the self-compacting principle, which will reduce CO₂ emissions and create prerequisites for increasing the durability of the material by reducing porosity and sorption capacity. Algorithm for reducing PC consumption in concrete is shown in Fig. 1.

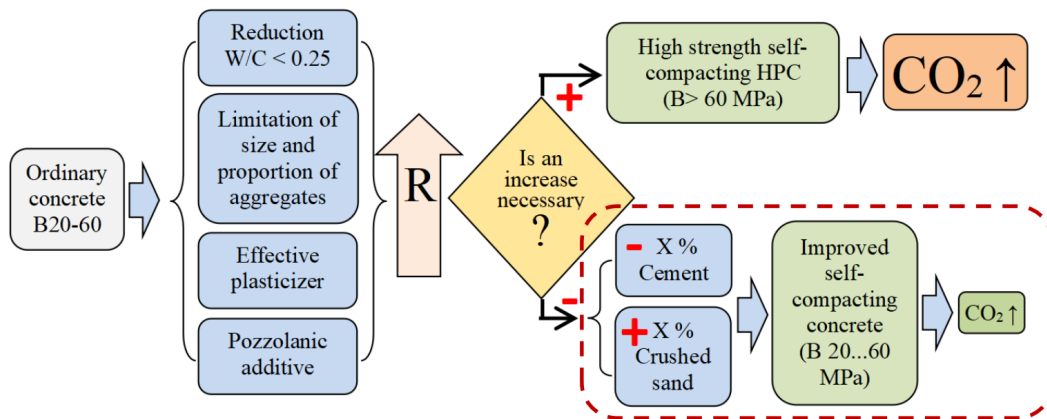


Fig. 1. Algorithm for reducing PC consumption in concrete.

This algorithm works as follows. Adding an effective plasticizer to ordinary concrete allows to significantly reduce the W/C ratio in the cement paste, while significantly changing its rheological properties by reducing flowability and viscosity. At the same time, an increase in the aggregate-containing concrete workability, with a decrease in cement paste viscosity will be significant only if the volume of PC fraction is commensurate with or greater than the volume of aggregate fraction. In this case, the aggregate particles will "float" in the cement paste, having a minimum number of contacts with each other and, therefore, having a minimal effect on the mixture viscosity. An increase in the PC content with a decrease in water consumption is achieved by introducing a mineral additive (gravel powder), which may include pozzolanic components oriented to strengthen the cement system, make it more stable and less susceptible to carbonation, leaching and sulfate corrosion due to the binding of free Ca(OH)₂ formed during cement system consolidation. The above techniques result in a 2-3 times increase in concrete strength. It is very important to prevent flocculation of PC particles by changing the charge of their surface with a superplasticizing additive, i.e. imparting pseudoplastic properties to the cement paste, making its behavior similar to a viscous liquid. This not only enables independent release of air involved in the mixture during mixing, but also provides more compact packing of PC and additives particles under gravity. Reducing the emptiness of the cement paste helps to reduce water consumption during mixture preparation and increase in strength, as well as increase concrete impermeability during operation. Thus, the above techniques are key to obtaining self-compacting HPC.

However, as mentioned earlier, increasing concrete strength is not always in demand. A huge number of concrete and reinforced concrete products are manufactured using concrete with a compressive strength of 20-60 MPa. But the ability of concrete to self-compact, reduce its porosity and, most importantly, reduce PC consumption instead of increasing in strength is beneficial from both economic and environmental positions. Therefore, there is a need to study the possibility of obtaining

CAC using self-compact technology, estimate the possible share of reducing PC consumption and develop a method for selecting a material composition with the required strength, suitable for use in the production process. As a methodological basis for designed concrete, the principle of sequential introduction of components with determination of their influence on the properties of the final material was tested. At the first stage, a mathematical model of the properties for fresh and consolidated cement paste was obtained and analyzed depending on the component combination. The presence of a mathematical model is necessary for choosing rational component combinations in cement paste and forming a mathematical apparatus for compositions calculating method. At the second stage, a change in the properties of this cement system was established upon the introduction of fine aggregate, and then upon the introduction of coarse aggregate.

Stage 1: Modeling the properties of fresh and consolidated cement paste.

To obtain a mathematical model of the properties for cement paste, a three-factor three-level experiment was carried out using the Box-Benkin matrix. The following factors were adopted as variable:

1. Fineness of the mineral additive (X_1), which was estimated by the specific surface area (SSA) value and varied in the range of 180–370 m²/kg with a step of 95 m²/kg.

Different natural and industrial components can be used as mineral additives in the multicomponent (composite) binders. Moreover, the use of mineral additives from raw materials with a high energy potential (i.e. high reactivity), according to literary sources, often provides a better result than the use of less reactive rocks. However, the use of various non-standard industrial and natural components is complicated by instability of the composition, limited availability, the need for preliminary processing before use. These issues require additional research, planned in further studies.

Quartz sand was chosen as a basic mineral additive to ensure mass application of the designed concrete and to create an effective cement-based system for further improvement, including studying self-healing issues. Quartz sand is available in all regions, and there is also the possibility of choosing sands with the required mineral composition, which makes it a universal basic additive. The disadvantage of quartz sand is its low grindability. Therefore, one of the research tasks was to determine the minimum required GS dispersion.

2. The degree of PC substitution by the mineral additive (X_2), i.e. GS amount, is expressed as a percentage of the PC weight (wt %). This parameter varied in the range of 80–300% with a step of 110 %.

The purpose of factor X_2 introducing into the experimental plan was to establish the maximum possible PC replacement by the GS in concrete for each required grade and strength class. This ensures the minimum PC consumption and the amount of greenhouse gas emissions associated with it per 1 m³ of concrete.

3. The amount of active mineral additive in the system (X_3), i.e. the CM content of expressed as a percentage of the PC (wt %). This parameter varied in the range of 0-15% with a step of 7.5%.

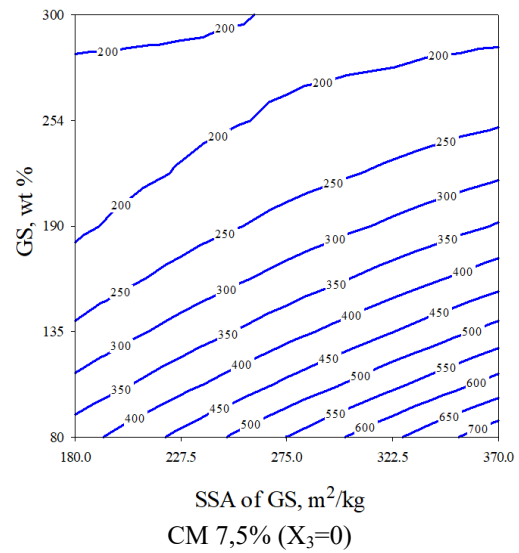
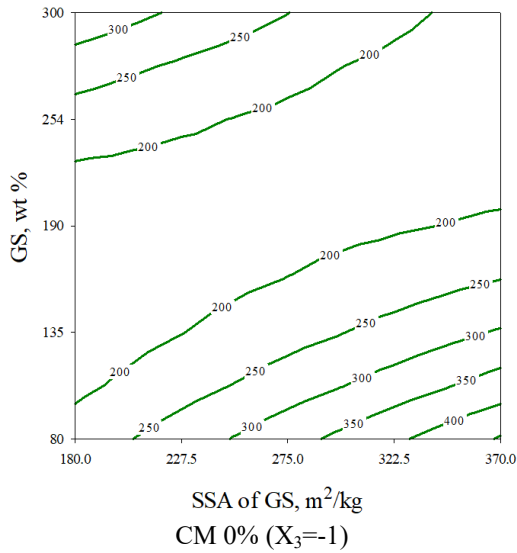
Factor X_3 assesses the need for CM introduction and sets its minimum required amount. Despite the fact that the components of the active mineral additive used are industrial waste, the CM modifier itself has a cost comparable to the cost of PC, so its justified savings will ensure a reduction in the cost of the mixture.

The following factors were adopted as output controlled ones: Y_1 is mixture viscosity, cSt (average value at 10, 20 and 30 rpm); Y_2 , is average density of cement paste, kg/m³; Y_3 , Y_4 , Y_5 are compressive strengths (MPa) at the age of 1, 7 and 28 days; Y_6 is water absorption (wt %) of hardened cement paste when saturated with water for 2 hours. The matrix design and experimental data are presented in Table 1.

Table 1. Matrix design and experimental data.

Mix ID	Variable factors						Y ₁ Viscosity, cSt	Y ₂ Average density, kg/m ³	Y ₃ R ¹ , MPa	Y ₄ R ⁷ , MPa	Y ₅ R ²⁸ , MPa	Y ₆ Water absorption, %
	Coded form			Original form								
	X ₁	X ₂	X ₃	SSA of GS, m ² /kg	GS content, (wt % of PC)	CM content, (wt % of PC)						
1	1	1	1	370	300	15	310	2174	11.8	38.1	48.5	2.8
2	1	1	-1	370	300	0	217	2119	11.2	32.2	43.1	6.8
3	1	-1	1	370	80	15	1202	2206	34.3	91.4	110.7	0.6
4	1	-1	-1	370	80	0	435	2240	39.6	103.5	133	0.2
5	-1	1	1	180	300	15	215	2079	8.8	38	57.4	6.8
6	-1	1	-1	180	300	0	244	2108	10.6	38	50.7	6.9
7	-1	-1	1	180	80	15	588	2230	32.8	83	113.4	0.4
8	-1	-1	-1	180	80	0	199	2192	37.5	77	84,8	3.4
9	1	0	0	370	190	7.5	216	2115	22.7	52.7	71.8	0.7
10	-1	0	0	180	190	7.5	324	2171	25	48	87.5	3.2
11	0	1	0	275	300	7.5	206	2141	11.7	33.6	41	4.2
12	0	-1	0	275	80	7.5	536	2178	45.2	99	121.3	0.9
13	0	0	1	275	190	15	339	2144	17.4	46.5	66.9	1.5
14	0	0	-1	275	190	0	279	2205	26.6	53	71.9	2.5
15	0	0	0	275	190	7.5	279	2148	24.4	49.5	68	2.4

The experimental data allowed plotting the most significant nomograms, with one of the variation factors being fixed at one of the levels. Fig. 2 shows the effect of the variable factors on the cement paste viscosity.



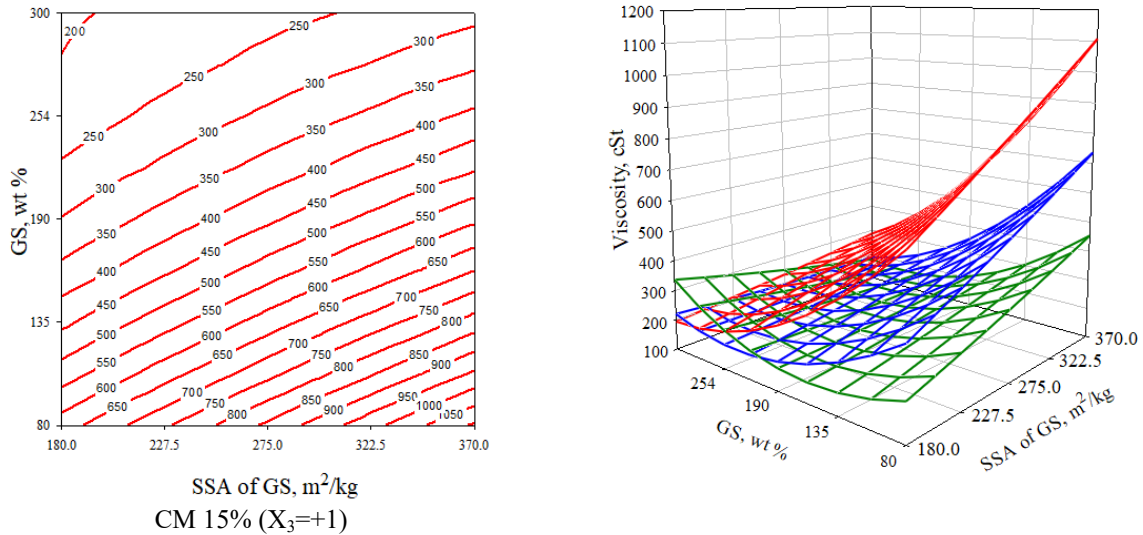
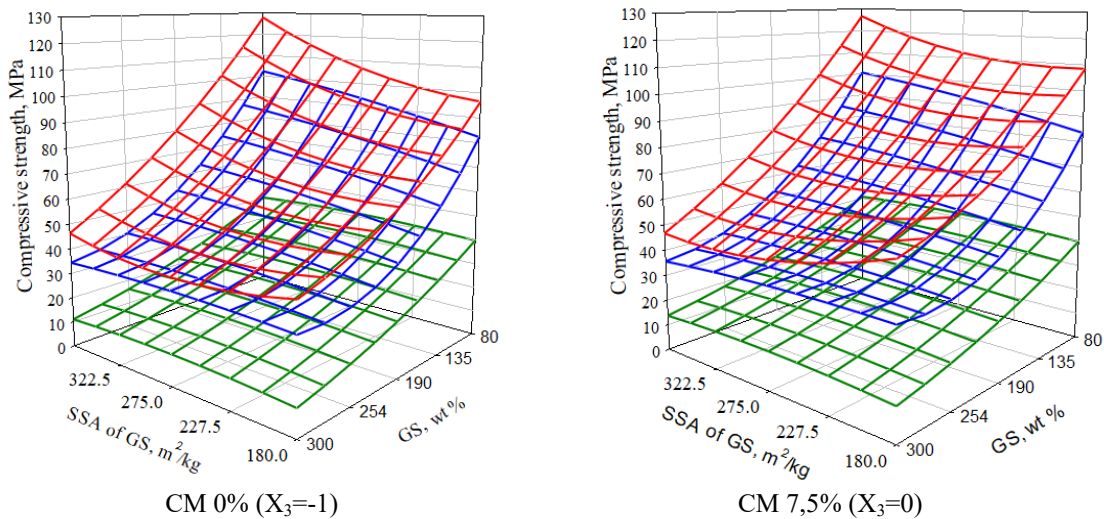


Fig. 2. Effect of variable factors on the cement paste viscosity.

The CM content (Fig. 2) significantly affects the viscosity of the resulting cement paste. The introduction of CM over 7.5%, most of the values are in the zone exceeding 300 cSt, where, according to preliminary experiments, obtaining suitable mixtures for use is difficult.

The lowest viscosity has mixes without CM. Moreover, values of less than 200 cSt are achieved in the central part of the GS content variation range. The effect of GS dispersion in this case is minimal. This creates prerequisites for the GS use with greater dispersion, when this is acceptable from the point of view of ensuring the required strength.

Fig. 3 demonstrates the variable factors effect on the cement paste strength at different ages.



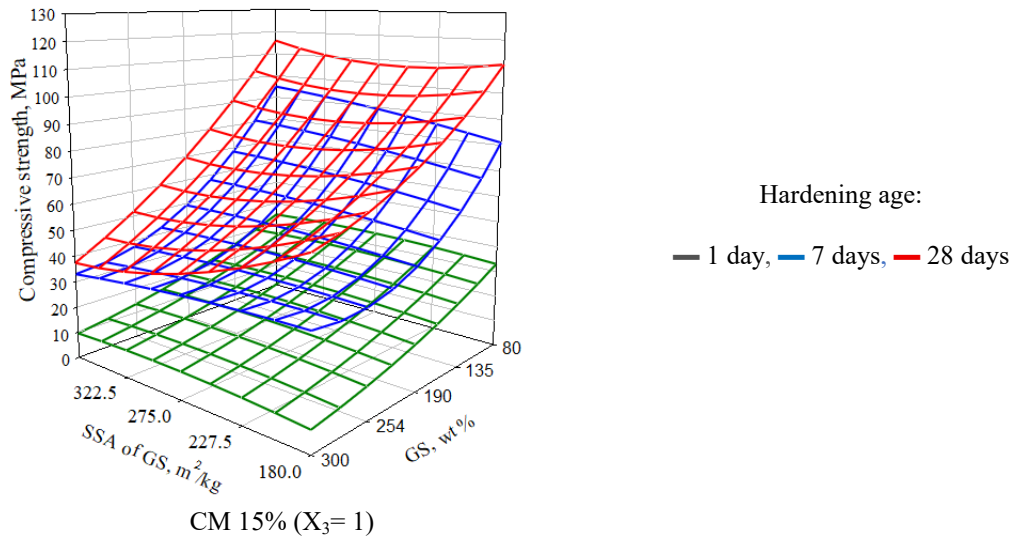


Fig. 3. Effect of variable factors on the cement paste strength at different ages.

At the age of 1 and 7 days, CM does not have a strong effect on the cement paste strength when decreasing and increasing its dosage relative to the average level of variation, therefore the corresponding nomograms are not presented.

At the age of 1 day, the greatest and almost linear effect on strength is logically exerted by GS content, characterizing the share of the decrease in PC content. The effect of SSA of CM is quite weak. There is some increase in strength until the average value of SSA of GS is reached, followed by stabilization of this parameter.

At the age of 7 day, a tendency appears for a linear decrease in strength with an increase in GS content to approximately 200% (1:2), with subsequent flattening of the characteristic response surface at a strength of 30-40 MPa. This creates a prerequisite for significant PC reduction when the low-strength concretes production due to the PC replacement with GS over 200% without a pronounced negative effect on strength.

Increasing SSA of GS has a noticeable effect on the strength of cement paste only in the area of the highest strengths with high PC content. The dependencies at the age of 28 days basically repeat the tendency that appeared at earlier age, but have a number of features, in addition to higher strength values.

1. The decrease in strength with increasing GS content becomes more linear with a decrease in the flattening degree of the zone with high GS content.

2. At the age of 28 days, the effect of CM on the strength of the cement paste becomes noticeable. The average CM dosage (7.5%) increases the strength by 20...25% in the area of the most economical mixes: GS content over 200% with minimum SSA (180...220 m²/kg). This trend is clearly visible in comparison with the nomogram for mixes without CM. Probably, the presence of CM strengthens the cement paste by binding free Ca(OH)₂ in cement systems with the lowest PC content and by increasing the hydration degree. This is important from the point of view of maximum efficiency of PC consumption within the framework of the sustainable development concept.

Increasing the SSA of GS over 220 m²/kg provides an increase in strength only for mixes with high PC content (GS content is 80...150%). However, this method can be used in practice to a limited extent due to the increased viscosity of the raw mixture in this zone. Probably, this disadvantage can be overcome by increasing the superplasticizer amount and, possibly, increasing the W/C ratio. However, this issue requires additional research. Based on the above, when designing concrete mixes within the influence of the selected variable factors, it is advisable to adhere to the choice of SSA of GS in the minimum range: 180...220 m²/kg, and with a CM content of 7.5%. In this case, the cement paste strength at the age of 1 and 28 days will be regulated by a linear dependence due to a change in the GS content.

Substituting into the regression equation (calculated on the basis of experimental data using MS Excel analysis), describing the dependence of strength on the variable factors $R_{\text{cement paste}}^{28} = 73 + 1.3 X_1 - 32.3 X_2 + 1.3 X_3 + 5.4 X_1^2 + 6.9 X_2^2 - 4.8 X_3^2 - 7.8 X_1 X_2 - 6.5 X_1 X_3 + 0.7 X_2 X_3$ (the degree of reliability of the model is $R^2 = 0.96$), the values of the fixed variables $X_1 = -1$ and $X_3 = 0$, the following equation has been obtained:

$R_{\text{cement paste}}^{28} = 77.1 - 24.5 X_2 + 6.9 X_2^2$, where $X_2 \in [-1; 1]$, which corresponds to a GS content of 80–300%. Refusal of the quadratic term will lead to an underestimation of the calculated result at the extreme points by 6...11.5%. Since this is insignificant when using concrete, this equation can be simplified to a linear one and presented as following:

$$R_{\text{cement paste}}^{28} = 77.1 - 24.5 X_2, \text{ where } X_2 \in [-1; 1],$$

or in natural units:

$$R_{\text{cement paste}}^{28} = 118.9 - 0.22 \text{ GS}, \quad (1)$$

where GS is the GS content of 80-300% with an SSA of 180–220 m²/kg, i.e. PC:GS ratio from 1:0.8 to 1:3.

The presence of an established linear dependence of the cement paste strength on GS content simplifies the design of concrete and allows determining the influence coefficients of fine and coarse aggregates.

Study of cement paste structure.

One of the advantages of HPC is its high performance, which is largely due to its low porosity and high density. To assess the quality of the resulting material structure, the average density and water absorption (by wt) dependences were plotted with a water saturation duration of 2 h (Fig. 4), and the microstructure was studied using electron scanning microscopy (Fig. 5).

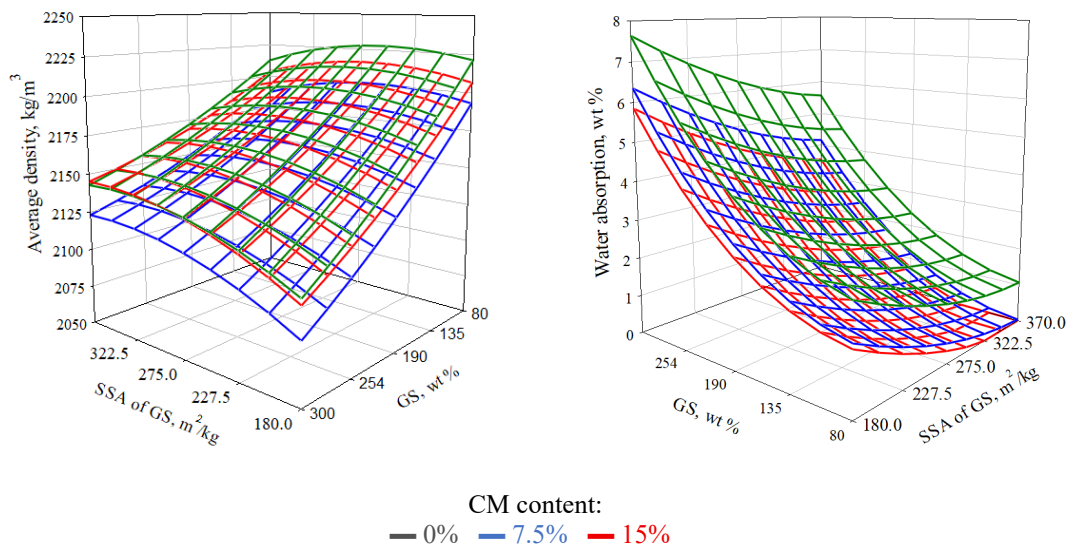


Fig. 4. Effect of variable factors on average density and water absorption.

As can be seen from the nomograms in Fig. 4, all mixes are characterized by water absorption of less than 8% and a dry density of 2050-2250 kg/m³. Reduced average density, maximum water absorption (7.5%) and, therefore, open and communicating porosity of the cement system are regularly observed with the highest PC replacement by GS with the lowest SSA, and without CM.

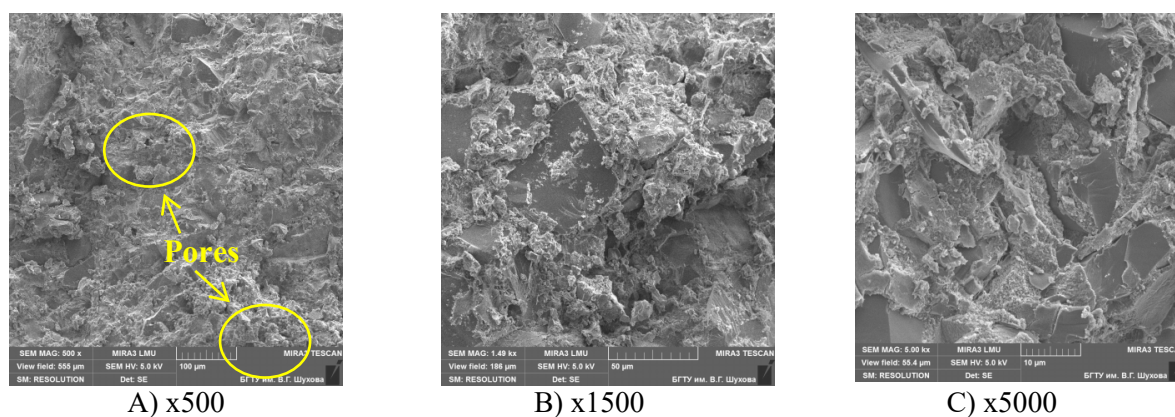


Fig. 5. Microstructure of cement paste with high substitution degree of PC by GS (300%), Table 1, Mix 11).

Low-magnification SEM photographs of the microstructure show pores of about 10 µm in size (Fig. 5 A), probably formed as a result of incomplete air removal during self-compaction. The cement paste structure has a high content of GS particles, but is quite compact and homogeneous at the macro level. At higher magnification (Fig. 5 B), it becomes noticeable that the cement paste filling the space between the GS particles is not sufficiently monolithic and contains voids. This is possibly due to the deficiency of cement paste, which ensures complete filling of the intergranular voids at low SSA and high GS content. It is also possible that the appearance of voids can be to some extent associated with the shrinkage effect. This assumption explains the increase in the mixtures viscosity (Fig. 2) in the region with the maximum GS content with minimum SSA value, which is especially noticeable in the free-of-CM mixes. Increasing the CM amount in the cement system gradually reduces the viscosity increase in the specified area, due to the increase in fine particles, due to GS introduction.

At maximum magnification (Fig. 5 C) it is clearly visible that the destruction of the cement paste structure occurs mainly with the separation of the binder from the GS particles, which confirms the relevance of searching for more effective fillers than GS, providing higher adhesion. This direction is planned to be developed in further studies.

Reduction of GS content (i.e. increase of PC consumption) causes compaction of cement paste and decrease of water absorption to 2.5-3.5%. At the same time, with reduction of GS content from 300% to 150–130%, at first, there is a rapid decrease in water absorption (porosity), and with further reduction of GS content to 80%, a tendency to flattening of the graph is observed (Fig. 4). In contrast to water absorption, the growth of average density of cement paste with reduction of CM content occurs almost linearly, which correlates well with the change in strength of the cement system (Fig. 3).

The microstructure of cement paste with higher PC content (Fig. 6) become more compact and homogeneous. The tendency to decrease the amount of GS particles at the fracture of the sample is clearly visible (Fig. 6 A). At higher magnification (Fig. 6 B) one can see continuous filling of intergranular voids with cement matrix, with a dense and homogeneous structure, without cavities. There is no deficit of cement matrix. GS particles are located from each other at a greater distance, practically without contact with each other.

This indicates a higher degree of separation of GS particles, which ensures maximum flowability of the mixture (Fig. 2). Viscosity in this range of values of the variable factors has a minimum value: 250 sSt and below. There are also single pores (shown in highlighting) with a clear spherical shape and a glossy inner surface. Pores of this type, even in large quantities, do not have a negative effect on the strength of the material, favorably affecting its frost resistance due to the provision of a reserve volume for displacing water from the capillaries.

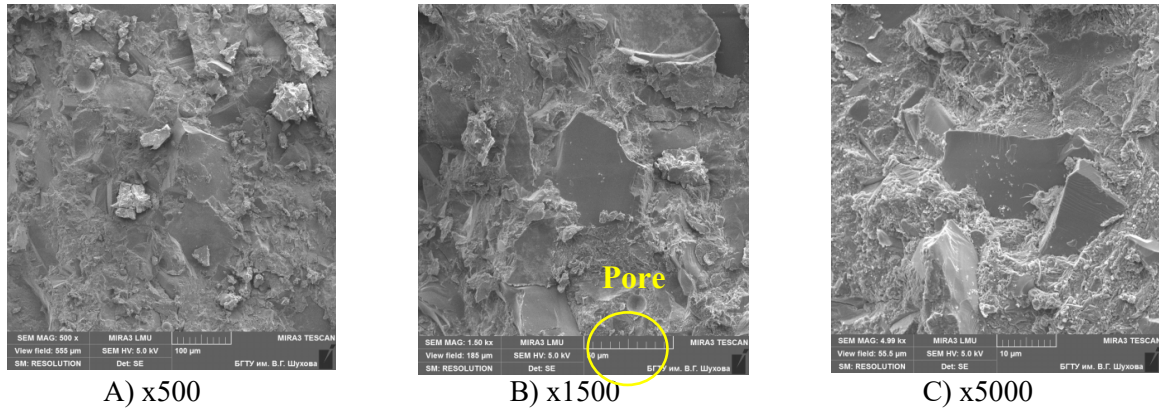


Fig. 6. Microstructure of cement paste with medium substitution degree of PC by GS (190%), Table 1, Mix 10).

In the SEM photograph with maximum magnification (Fig. 6 C) the destruction of the material with partial separation of the cement matrix from the surface of the GS particles is also noticeable, and a high packing density of new formations is observed, which explains the high strength of the cement paste: about 60-80 MPa (Fig. 3) with a CM content of 7.5%. Mixes with maximum PC consumption are characterized by an average density close to the maximum value: more than 2180 kg/m^3 and low water absorption: less than 2% (Fig. 4). At the same time, due to the increase in PC content with high sorption capacity in relation to the plasticizer, the viscosity of the mixture increases from 250 to 400 sSt. Probably, the increase in viscosity can be partially compensated by increasing the dosage of the superplasticizer, recorded in these studies as a constant (0.6%). It is also likely that the viscosity increase is inevitable due to the significantly higher SSA of PC particles compared to GS, which can only be compensated for by increasing the water consumption. The cement paste strength for the noted input parameters reaches 90-100 MPa.

There is also the possibility of further reducing in water absorption to almost zero by increasing the SSA of GS to values of PC (Fig. 4) and increasing the CM content to 15%. In this case, the grain composition of the mixture (PC + CM + GS) is close to the maximum possible particle packing density, and the colmatation of residual pores occurs due to the pozzolanic reaction. Despite the fact that such mixes are not of great interest within the framework of the problem being solved due to the increased viscosity, energy and resource intensity, they can be used in the future to solve special problems, for example, designing concrete for protective layers or operation in aggressive conditions.

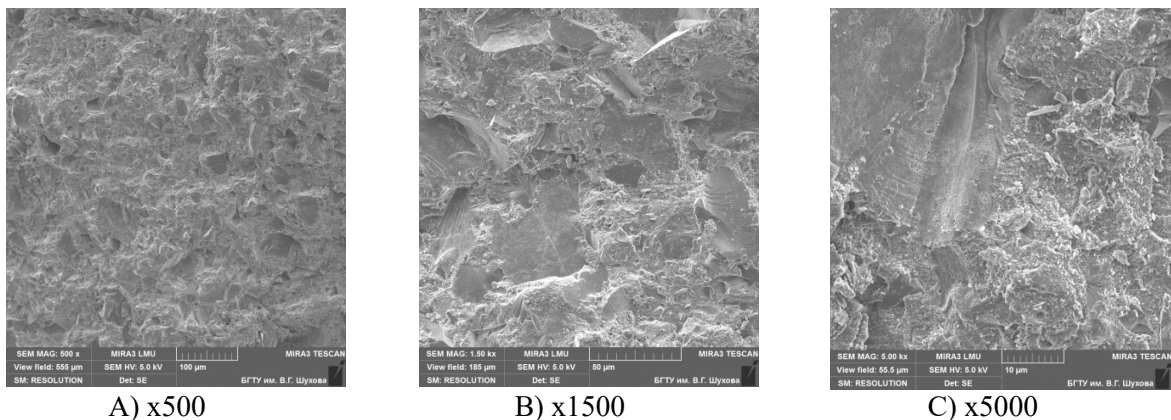


Fig. 7. Microstructure of cement paste with low substitution degree of PC by GS (80%), (Tab. 1, Mix 12).

The microstructure of the low GS-bearing cement paste (80%) at low magnification (Fig. 7 A) is characterized by a uniform distribution of GS particles separated by quite large areas of crystalline new formations. At higher magnifications (Fig. 7 B, C) it is seen that a significant part of the sample cross-section is formed by the cement matrix with a compact monolithic structure, without visible pores or other defects. A high density of the "cement matrix – GS particles" contact zone with a poorly defined phase boundary is observed. Despite the higher strength, the high degree of filling of the cement system with new formations, rather than GS particles, increases the risk of developing autogenous shrinkage deformations, which are potentially dangerous for high-density structures. And although the resulting concretes, within the accepted ranges of variation of factors, are quite stable and do not demonstrate a tendency to develop internal destruction, it is still more promising to increase the strength of the cement paste without an excessive increase in PC consumption due to the use of more reactive fillers. As already mentioned, this will also contribute to increasing the cost-effectiveness and environmental friendliness of the final concrete material.

Another important trend monitored on the water absorption graph (Fig. 4) is the effect of CM content. At all points of the value field for mixtures without CM (CM=0%), water absorption is higher by $\approx 1\%$, even despite the higher PC content. At the same time, an increase in CM content from 7.5 to 15% practically does not lead to a decrease in water absorption (except for the case, considered earlier). Probably, this can be explained by the mechanism of CM action, based on the binding of Ca(OH)_2 released by PC. At a CM dosage of 7–8%, the main amount of Ca(OH)_2 available for the reaction is bound in low-basic hydrosilicates, which ensures compaction of the cement system and a decrease in its water absorption. For a higher CM dosage, there is not enough amount of free Ca(OH)_2 in the cement system. These facts can serve as a convincing justification for CM introducing into the cement system at a rational amount of 7.5-8% (wt % of PC). It should be noted that when PC using from another manufacturer, with a different alite content as the main source of Ca(OH)_2 , the CM content should be adjusted.

Stage 2: FAC production.

When FAC production based on the designed "PC + CM + GS" binder, ordinary quartz sand (S) with $M_k=1.5$ with non-standardized grain composition was used. The S amount is of 1; 1.2; 1.4; 1.6 mass fractions from the binder. Increasing the S content reduces the cost of the concrete mix, but potentially negatively affects its flowability, which in this case was estimated by the mini-cone flow diameter, as well as on the basis of the FAC strength. The results are shown in Fig. 8.

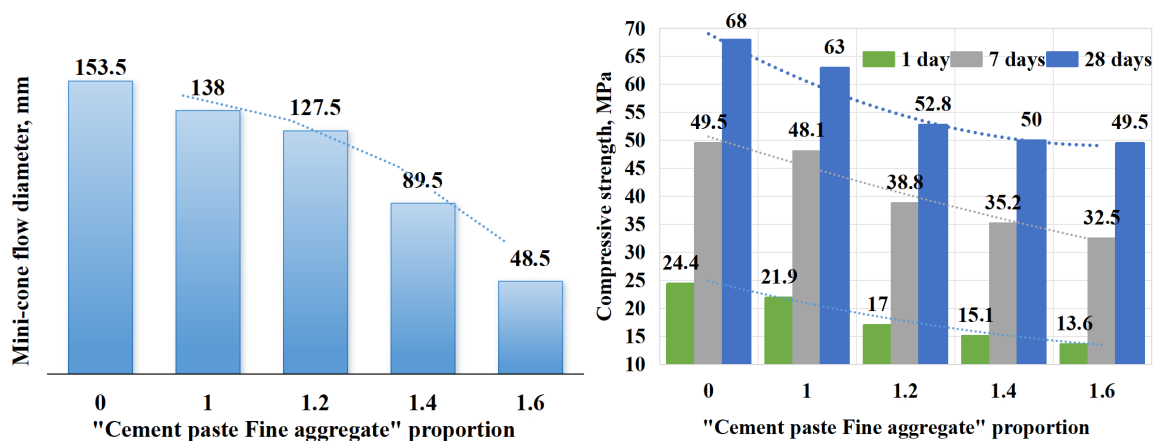


Fig. 8. Effect of quartz sand on FAC characteristics.

As can be seen from the graphs Fig. 8, S introduction in the amount of 1 proportion (wt % of the binder), in comparison with cement paste (without S), has virtually no effect on the viscosity of the concrete mixture and FAC strength at all ages of hardening. This is due to the fact that there is a significant expansion of the aggregate grains and the cement paste can work as an independent structure without transferring a significant portion of the stresses to the aggregate particles.

Increasing the S proportion to 1.2 slightly ($\approx 7 \dots 10\%$) increases the viscosity of the concrete mixture and FAC strength at the age of 1 day ($\approx 10 \dots 17\%$). At a higher age, the decrease in strength in comparison with a 1: 1 mix is 20 ... 23%.

With an increase in the S proportion above 1.2, a rapid increase in viscosity begins (a decrease in the mini-cone flow diameter). FAC strength monotonically decreases with an increase in the S content above 1.2. Thus, for further research, the S content of 1.2 was used.

Stage 3: CAC production.

For CAC production, crushed quartzite sandstone of 5–10 mm fraction was used. The effect of its amount on the concrete mixture flowability and CAC strength was studied. To eliminate the effect of possible dustiness of the particle surface, the crushed stone (CS) was washed before use, then dried to remove free water from the particle surface and then used to prepare the concrete mixture. This method is aimed at eliminating excessive adhesion of cement paste due to dehydration of CS upon contact with the surface of the grains, and, as a result, to prevent a negative impact on the mobility of the concrete mixture, as well as to ensure good adhesion of the cement matrix to the CS. In practice, with low CS dustiness, drying can be replaced by moistening the CS surface in a concrete mixer to approximately 0.3 ... 0.5% humidity. The concrete mixture was prepared in three stages. 1) Preparation of cement paste. 2) Introduction of fine aggregate with moisture content of 1% (by wt %). 3) Addition of CS to the mixture. Mini-cone flow diameter was determined for the obtained mixture, and then samples of 7×7×7 cm in size were molded.

Based on preliminary experiments, boundary values of CS consumption were determined to ensure obtaining material with acceptable quality: lower level – 88% (C1), upper level – 1.04 (C2). The component composition of the cement paste was adopted constant with the following ratio of components (by wt %): PC : CM : GS = 33.7 : 2.5 : 63.7. W/C = 0.20; superplasticizer dosage is 0.6%; quartz sand consumption is 120%.

As can be seen from Fig. 9, changing the CS content within the specified values has a noticeable effect on the mixture flowability, and an insignificant effect on the CAC strength.

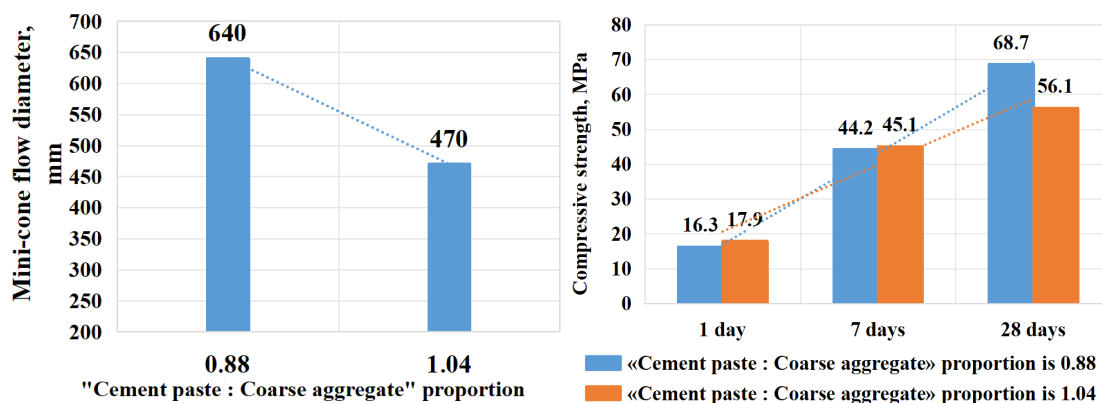


Fig. 9. Effect of CS content on mixture flowability and CAC strength.

Depending on the required mixture flowability and taking into account the reduced effect on strength, the CS amount can be taken according to this relationship. For further studies, the CS proportion was taken as 0.9 (by wt % of the binder).

«Cement paste : Coarse aggregate» proportion is 0.88

Definition of matching coefficients.

Due to the use of concrete specimens with different sizes and component compositions at different stages of hardening, an additional experiment was carried out to design the methodology for selecting concrete mixes to establish conversion factors for the strength ratio of specimens obtained on cubes with of 2×2×2 cm and 7×7×7 cm, differing only in the presence of the corresponding aggregate. The

experiment used a mix of CAC (in mass fractions): PC = 0.0792; CM = 0.0059; GS = 0.2161; W = 0.0602; S = 0.3614; CS = 0.2771. Moreover, for cement paste only "PC + CM + GS" binder was used in the specified proportion; for FAC, the specified quartz sand was additionally introduced to the binder; for CAC, all of the above components were used. Specimens with dimensions of 7×7×7 cm and 2×2×2 cm were molded. Hardening of the specimens occurred under the same conditions. The test results are shown in the diagram (Fig. 10).

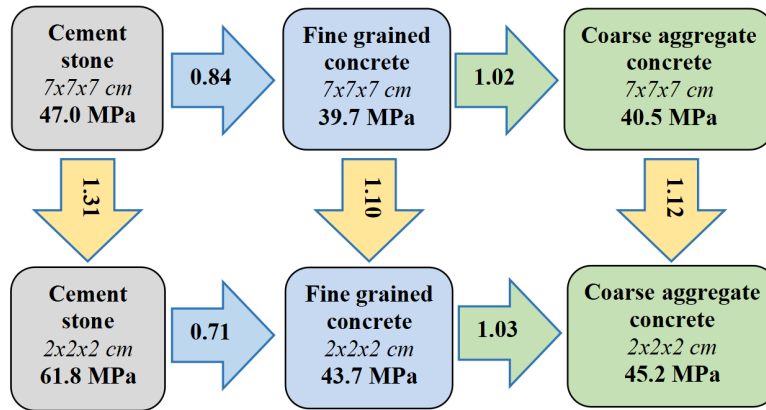


Fig. 10. Effect of component composition and sample size on compressive strength.

As can be seen from Fig. 10, for all cases, the decrease in the sample sizes naturally leads to an increase in strength. The greatest effect, about 30%, is observed for free-of-aggregate mixes. FAC mixes have similar transition coefficients at the level of 10-12%. The transition from cement paste to FAC is accompanied by the most significant decrease in strength by 16 and 29% depending on the sample size. At the same time, the introduction of CS occurs practically without affecting the concrete strength: the increase is 2–3%.

Design of concrete mixtures calculation method.

Summarizing the previously obtained data, an algorithm was developed for designing self-compacting concrete mixes of various grades in strength for the raw materials used in the work, and the accepted limitations and assumptions.

The initial data are the required concrete grade in strength at the age of 28 days and the flowability of the mixture. As an example, concrete with grade class of B30 will be considered. The CS proportion is taken to be 0.9, which corresponds to a mini-cone flow diameter of 600...640 mm.

The change in strength when CS introducing into the CAC mixture (Table 4) is positive (hardening is observed) and is expressed by a coefficient of 1.02. Due to the fact that this coefficient is ≈ 1 , to simplify further calculations for CS with a size of 5–10 mm, this coefficient was taken to be = 1. When CS using of a different size or another aggregate, the transition coefficients should be clarified. Based on the specified concrete grade in strength and the strength variation coefficient (12.5%), the required concrete strength was determined as $R_y = 30 / 0.778 = 38.6$ MPa. Thus, the required FAC strength of the "Binder : Sand" mixture = 1: 1.2 will also be equal to $R_{FAC} = 38.6$ MPa.

Next, the required strength of the "PC + CM + GS" binder was determined. The change in strength when S is introduced into the binder (Table 4) is negative and is expressed for ordinary quartz sand by a coefficient of 0.84. Thus, the required strength of the "PC + CM + GS" binder should be $R_{binder}^{28} = 46.0$ MPa.

However, since the binder strength modeling within the framework of the studies was performed on 2×2×2 cm cube samples, it is necessary to apply the conversion factor from 7×7×7 cm samples to 2×2×2 cm samples, which for the binder, according to Table 4, is $K_{73 \rightarrow 23} = 1.31$. Consequently, the required strength of the binder for 2×2×2 cm samples will be as a following: $R_{binder}^{28} = 60.3$ MPa.

Next, the composition of the binder that provides the required strength is determined. Using the obtained dependence $R_{\text{binder}}^{28} = 118.9 - 0.22 \text{ MPa}$, the GS proportion with SSA of $180 \text{ m}^2/\text{kg}$ was calculated to obtain the binder with a strength of 60.3 MPa .

$\text{GS} = (118.8 - R_{\text{binder}}^{28}) / 0.22 = (118.8 - 60.3) / 0.22 = 58.5 / 0.22 = 265\%$ of PC content, i.e. $\text{PC:GS} = 1 : 2.65$.

Using the previously indicated ratios, the consumption of all components (by wt) per unit volume of concrete mixture is determined. The total ratio of components, according to the calculation given, will be as follows:

$(\text{PC} : \text{CM} : \text{GS180}) : \text{W} : \text{S} : \text{CS} = (1 : 0.075 : 2.65) : 0.2 : 1.2 : 0.9$, or

$\text{PC} : \text{CM} : \text{GS180} : \text{W} : \text{S} : \text{CS} = 0.0806 : 0.0061 : 0.2145 : 0.0602 : 0.3614 : 0.2771$.

Over 100% of the binder mass, the amount of superplasticizer (0.6%) and water consumption to ensure 1% moisture content of quartz sand are taken.

The calculated average density of the concrete mixture is determined using the data on the mass ratio and the actual density of the components, and in the example considered, is 2436 kg/m^3 .

Concrete mixtures calculation method testing.

According to the designed method, component compositions were calculated and concretes of strength classes B20 and B30 were produced. These classes of concrete are the most in demand in construction and are recommended for practical use. The concrete mixtures were prepared as follows: $7 \times 7 \times 7 \text{ cm}$ cubes were formed without forced compaction; samples were stored in an aqueous medium at ambient temperature. The calculated concrete mixes are presented as diagrams (Fig. 11).

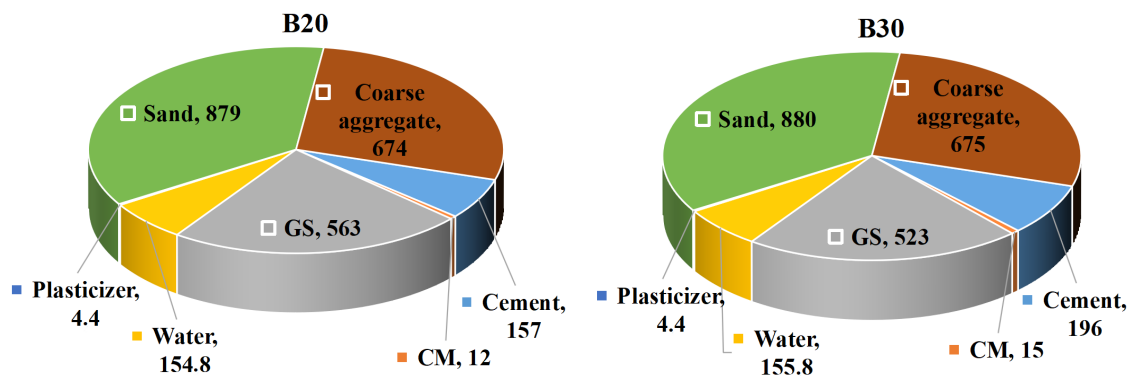


Fig. 11. Calculated concrete mixes of strength classes B20 and B30 (component consumption is presented in kg per 1 m^3 of concrete mixture).

The studied mixes have the same aggregate and water content, and actually differ only in the ratio of components in the binder, primarily in PC:GS ratio. This approach allows to easily adjust the concrete strength without significantly affecting its macrostructure, determined by the aggregate content.

After hardening and testing of concrete, it was found that the $7 \times 7 \times 7 \text{ cm}$ cube samples with a predicted strength class of B20 have a real strength of 30.9 MPa . Taking into account the standard coefficient of 0.85, established by the Russian Standard GOST 10180 and allows to recalculate the strength values for standard $15 \times 15 \times 15 \text{ cm}$ cubes. In this case, the strength is 26.3 MPa . With a standard strength variation coefficient of 13.5%, this strength value corresponds to the predicted strength class of B20, exceeding the required value by 2%. Similarly, for the given class B30, the actually achieved strength on $7 \times 7 \times 7 \text{ cm}$ cubes is 47.8 MPa , which is 5% higher than the required value for class B30. Thus, the actual strength values of the obtained concretes correspond to the predicted ones.

The economic feasibility of using the proposed solutions is due to a decrease in PC consumption and a corresponding decrease in the cost of production. Fig. 12 shows data on PC consumption for concretes obtained using the developed technology in comparison with the standard PC consumption for similar strength classes for concretes with a plasticizer (according to Russian Standard GOST 27006-2019).

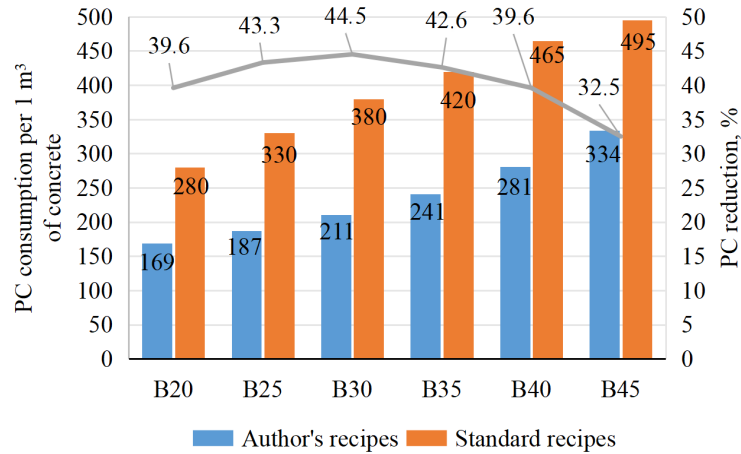


Fig. 12. Comparative PC consumption for concretes of different classes in strength of ambient hardening.

As can be seen from Figure 12, the developed method provides a reduction in PC consumption by 30-45% compared to traditional superplasticizer bearing concrete. It should be understood that the practical implementation of the proposed solutions will require additional costs for GS, which occupies a significant proportion of the binder, as well as the purchase, installation, adjustment and maintenance of a mill for S grinding and a special mixer for preparing cement paste. It is also necessary to further study the issues of applicability of the developed mixes for various products and technologies for their production.

4. CONCLUSIONS

The source of a significant amount of CO₂ emissions in a global scale is the production and consumption of PC, the reduction of which is an urgent task for scientists. In this regard, a promising method for increasing the degree of compliance of coarse aggregate concrete with the requirements of the modern sustainable development concept is the use of internal PC resources, leading to a reduction in PC cement consumption in the most popular classes of concrete strength: B20–B50, and, as a consequence, a decrease in CO₂ emissions in the construction industry as a whole. This is achieved by implementing the principles of self-compacting concrete at the micro and macro levels, significant water reduction, a high proportion of filling the binder with finely dispersed mineral additives. The choice of a mineral additive and its dispersion also have a significant impact on both the energy intensity and the effectiveness of PC substitution. The use of GS as a mineral additive in this manuscript is due to the requirements of concrete mixture stability and widespread availability, which allows for the practical application of the obtained results with minimal barriers and to contribute to the reduction of CO₂ emissions. In addition, it allowed to realize the potential of increasing the efficiency of PC use only due to the improvement of the microstructure of concrete by self-compactability and low water content. The designed efficient binder is necessary for the search and transparent tracking of the influence of other more energetic mineral additives based on technogenic products and rocks in different stages of metamorphism, the selection of which will be made in subsequent studies.

Increasing the density and improving the quality of the cement paste structure with a reduction in PC consumption and increasing the efficiency of its use explains the need to assess its ability to self-

heal micro-cracks that occur during operation. The resulting cement system, by its set of properties, is an ideal object for testing known self-healing methods and developing new ones, which will further increase the service life of concrete. This aspect should be considered an important area of further research and an additional reserve for reducing the negative impact of construction on the environment.

When designing binder and concrete compositions within the studied field of influence of factors, use the minimum SSA of GS: 180 ... 220 m²/kg, and CM in the amount of 7.5% (by wt % of PC). In this case, the strength of the binder is expressed by the following equation:

$R_{\text{binder}}^{28} = 118.9 - 0.22 \text{ CM}$. This ensures the strength of the binder from 60 to 105 MPa at 28 days of age and from 12 to 40 MPa at 1 day of age. The developed method for designing self-compacting concrete mixes allows obtaining concrete of the required strength with a reduction in PC consumption by 30-45% compared to traditional superplasticizer-bearing concretes of similar strength. The use of raw materials with different characteristics requires clarification of the transition factors before applying the developed method.

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